FINAL REPORT

Changes in forest vegetation and fuel conditions 15 years after prescribed fire

JFSP PROJECT ID: 15-1-07-6

December 2019

Malcolm North
USFS PSW Research Station, Davis, CA 95618

Harold Zald
Humboldt State University, Arcata, CA 95221

Brandon Collins
U.C. Berkeley and USFS PSW Research Station, Davis, CA 95618

Matthew Hurteau
University of New Mexico, Albuquerque, N.M. 87131

Table of Contents

List of Figures

List of Tables

List of Abbreviations/Acronyms

Abco: *Abies concolor* (white fir)
Abma: *Abies magnifica* (red fir)
BC: Burn/Caspo treatment (all trees >10" and <30" removed followed by a Rx burn)
BN: Burn/No thin treatment (Rx burn, no thinning applied)
BS: Burn/Shelterwood (all trees >10" removed except for 8 trees/ac left evenly spaced, followed by a Rx burn)
Cade: Calocedrus decurrens (incense cedar)
UC: Unburned/Caspo treatment (all trees >10" and <30" removed)
UN: Unburned/No thin treatment (Control)
US: Unburned/Shelterwood (all trees >10" removed except for 8 trees/ac left evenly spaced)
Pije: *Pinus jeffreyii* (Jeffrey pine)
Pila: *Pinus lambertiana* (sugar pine)

Keywords

Forest vegetation, fuels treatment, mechanical thinning, prescribed fire, forest resilience

Acknowledgments

We thank the Teakettle Field Crews during the summers of 2016, 2017, and 2018 who tirelessly collected data under often difficult conditions. We are also grateful to the Sierra National Forest personnel who have been instrumental in all of the treatment applications and facilitating our interactions with the Supervisor's Office in Clovis, CA.

Abstract

Early assessments of the different fuel treatments implemented at Teakettle suggested understory thinning and burning produced the most resilient forest conditions. However, this assessment did not hold up in the longer-term (15-17 years after treatment) trends in ecosystem responses. All treatments after 15 years were dominated by high shrub cover while herbaceous cover and plant diversity had decreased. Shrub cover response was related to tree density, probably because lower densities had higher understory light environments. Some of the increase in understory light was due to tree mortality from the 2012-2016 drought, complicating whether changes in canopy cover were due to original fuel treatments or more recent drought and onset of bark beetle damage. Drought induced tree mortality varied by species and size class with fir, both small and large sizes, and sugar pine, just large sizes, having the highest rates. While thinning generally decreased mortality, with the exception of red fir, burning increased mortality rates among large white firs and sugar pines. For tree regeneration, longer term trends, contrary to initial (1-4 years post treatment) response showed a decrease in white fir, but an increase in incense cedar and Jeffrey pine. Likewise, while initially there was greater heterogeneity in regeneration densities, after 15 years, all treatments had lower heterogeneity than in pre-treatment conditions. Thinning treatments resulted in large increases in tree growth rates, while burning alone resulted in initial declines. During the 2012 – 2016 drought, radial growth declined in all treatments, but was still noticeably greater than pretreatment levels for thinned treatments, indicating that thinning resulted in a persistent increase in growth for residual trees that was sustained during the drought. Radial growth response during the drought was comparable for understory and overstory thinning. This suggests a wide range of stand-level thinning intensities may result in similar persistent increases in growth not reversed by drought. Lastly, species differences in growth response during the drought appeared to become more apparent with increased thinning intensity. Tree DBH, and change in growth space from pretreatment to 2011 were the most important predictors of growth response during the drought. A more robust analysis using Random Forest found tree level attributes such as size and growing space, not stand level thinning intensity, may be driving growth responses. Fuel conditions and potential fire behavior suggested, as expected, that the untreated control had the highest crown fire potential. The understory-thin + burn has the second highest potential, given the combination of moderately high shrub cover and moderate tree density; while the overstory-thin + burn has high potential surface fire behavior, but given the low residual tree density and the high height-to-live-crown of the residual trees has a reduced potential for overstory tree torching.

Overall our results suggest that the Sierra Nevada's high productivity and vigorous endemic fire-adapted shrubs necessitate that once fire is used, it must be repeatedly employed to

initially restore and subsequently maintain a diverse fuel, understory, and microclimate environment.

Objectives

For this project our research focused on how vegetation, fuel conditions, and tree radial growth responded to a 2001 prescribed fire and how this response varied spatially and temporally over the last 15 years. Identifying what is causing differences in vegetation and fuels response, we focused on investigating what stand conditions and microsite conditions are associated with areas within burn treatments that are not fuel and shrub dominated, and in which trees are thriving. During 2012-2016 California experienced one of the most severe droughts of the last 500 years. We wrote our proposal in 2014 before we were aware of the extent and severity of this drought, which resulted in 20-30% mortality of most species. We, therefore, also assessed which trees were thriving not only after the 2001 prescribed fire, but also through the drought. In the burn treatments, we were particularly interested in what site and forest conditions may increase resilience to drought? How should mixed conifer forests be managed to instill greater resilience to likely future drought and bark beetle mortality?

Background

Eighteen years ago, the Teakettle Experiment applied a replicated full factorial experiment comparing mechanical thinning and prescribed burning effects on mixed-conifer ecosystem processes. We initially determined that the burn and understory thin (i.e., the B.C.) treatment was most effective at restoring ecosystem structure and processes. However, after several years all of the burn plots became fuel loaded (from dead ladder fuels), had highly homogenized understory conditions of >85% shrub cover (principally *Ceanothus cordulatus*), tree regeneration became dominated by shade-tolerant, fire-sensitive species (fir and incense-cedar), and some of the largest trees died. We wanted to investigate what stand and microsite conditions are associated with this reduction in resilience. In addition, we wanted to assess drought mortality and determine what factors might be associated with higher tree survivorship.

The Teakettle Experiment is a replicated, full factorial design crossing burning (burn, no burn) and thinning (no thin, understory, overstory) treatments on 18 ten-acre plots of mixed-conifer forest. Within each plot all trees, snags, and logs are tagged and mapped, and fuels and understory conditions are measured at 402 gridded, monumented sampling points. More than 70 publications have documented changes in forest conditions and carbon dynamics in this experiment (http://teakettle.ucdavis.edu).

Results and Discussion

We’ve organized our results by the analyses outlined in the original proposal. All of the analyses have now been completed, but the stages at which the results have been written up and peer reviewed, vary with project.

Q1) What vegetation and fuel conditions are produced by different management treatments at three time periods: 1-4 years, 9-11 years and 15-17 years?

Understory shrubs and herbs

For the initial response (1-4 year period) following treatment, we found mechanical thinning and prescribed fire reduced fuels including litter depth increasing the availability of bare ground that resulted in an initial increase in herb cover. The reintroduction of surface fire as a disturbance process promoted plant diversity in Teakettle's mixed-conifer forest after nearly a century of fire exclusion. Teakettle historically had a 17-year fire return interval but had not burned since 1865. Fuel loads (Innes et al. 2006) covered much of the forest substrate, limiting germination sites. Both richness and evenness increased in the burn treatments, with those increases being greatest in the treatments with higher intensity fire. Fire intensity was directly related to the amount of activity fuel produced by the thinning treatments (i.e., increasing from no thin, to understory thin to overstory/shelterwood thin) (Innes et al. 2006). These results were published in Wayman and North (2007) and including an ordination analysis of the whole plant community suggesting that changes over time were greatest for the burn/thin combined treatment as fuel loads were reduced.

When we compared understory conditions from our intermediate (9-11 years after treatment) sampling, we found that much of the diversity and herbaceous cover was significantly reduced in treatments that included fire. Litter depths and particularly shrub cover had increased, resulting in a more homogenous understory community dominated by the shrub whitethorn ceanothus (*Ceanothus cordulatus*). Fuel loading in the burns had increased from litter cast but also the addition of small, dead trees killed in the prescribed burn. In contrast, in the thinning treatments, ground cover dominated by slash and litter activity fuel had limited the response of shrubs while also reducing herb cover. However, observation suggested that decomposition was opening up more of the soil surface for understory plants, it was just not clear whether shrubs or herbs would capitalize on this available substrate.

In our final sample period (15-17 years after treatment), all treatments were dominated by high shrub cover while herbaceous cover and plant diversity had decreased. Although we did not systematically test shrub origin, digging up and cutting some of the whitethorn ceanothus suggested that re-sprouting was responsible for the ceanothus response in burn plots, while younger individuals suggested ceanothus in the thin-only treatments may have come from seed. Research has suggested some shrubs such as ceanothus can retain viable seed in the soil bank for 50-100 years. We documented these changes in the publication by Goodwin et al. (2018). In the paper we also reported an interesting finding that shrub cover response was related to tree density, probably because lower densities had higher understory light environments. Some of the increase in understory light was due to tree mortality from the 2012-2016 drought, complicating whether changes in canopy cover were due to the original fuels treatment or more recent drought and onset of bark beetle damage.

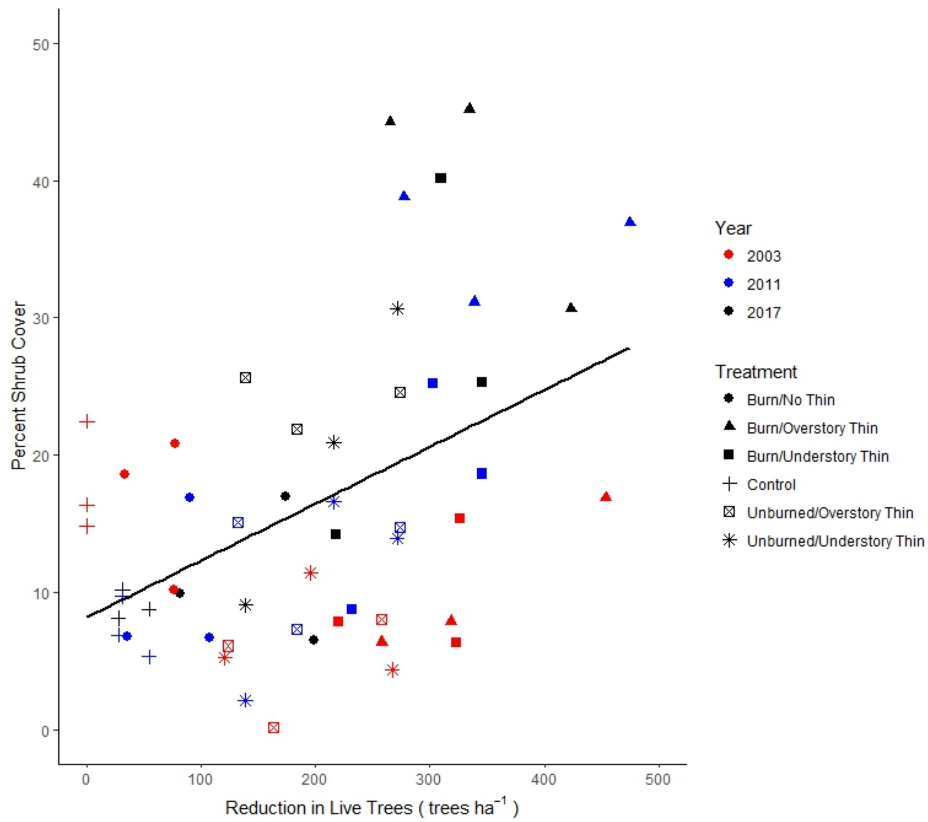

Figure 1: The relationship (Spearman's Rho) between the average shrub cover for 2003, 2011, and 2017, and the reduction in live tree density from 1999 for each of the three post-treatment sampling years by treatment type.

Mechanical thinning is often considered a partial fire-surrogate treatment because it reduces tree density and canopy cover, mimicking some of the structural effects of a fire treatment, but produces different fuel conditions (i.e., an increase in surface fuels compared to burn's decrease). However, initially we found thinning alone failed to reintroduce the functional processes of fire, including the reduction of litter and surface fuels, that increase understory diversity and cover. Treatments that incorporated fire experienced a fuel reduction in litter depth and coarse woody debris, increasing the amount of bare ground available for herb germination, while thin-only treatments reduced available bare ground. Increases in herb cover were also associated with an immediate reduction in shrub cover in all treatments, although the reduction was higher in thin and burn treatments (Burn/Overstory Thin = -78%, Burn/Understory Thin = -71%) than the reduction in thin-only treatments (Overstory Thin only = -68%, Understory Thin only = -45%) due to mechanical damage. While the effects of burning and thinning treatments on the understory diverged immediately after treatment, 17 years later, increased shrub cover and litter and woody fuel inputs reduced the bare ground substrate available for germination resulting in a decrease in herb cover.

Our results suggest that the Sierra Nevada's high productivity and endemic fire-adapted shrubs with vigorous re-sprouting and soil seedbank mechanisms, necessitate that fire, once used, must be repeatedly employed to restore and maintain a diverse understory plant community. We do caution, however, that less productive dry forests, with lower fuel input rates and different shrub species may not experience as rapid a decline in herbaceous cover as we documented.

Q2) Currently how resilient are these different fuels reduction treatments to drought (mortality and reduced growth)?

First, we've examined tree mortality, parsing dead trees by size and species.

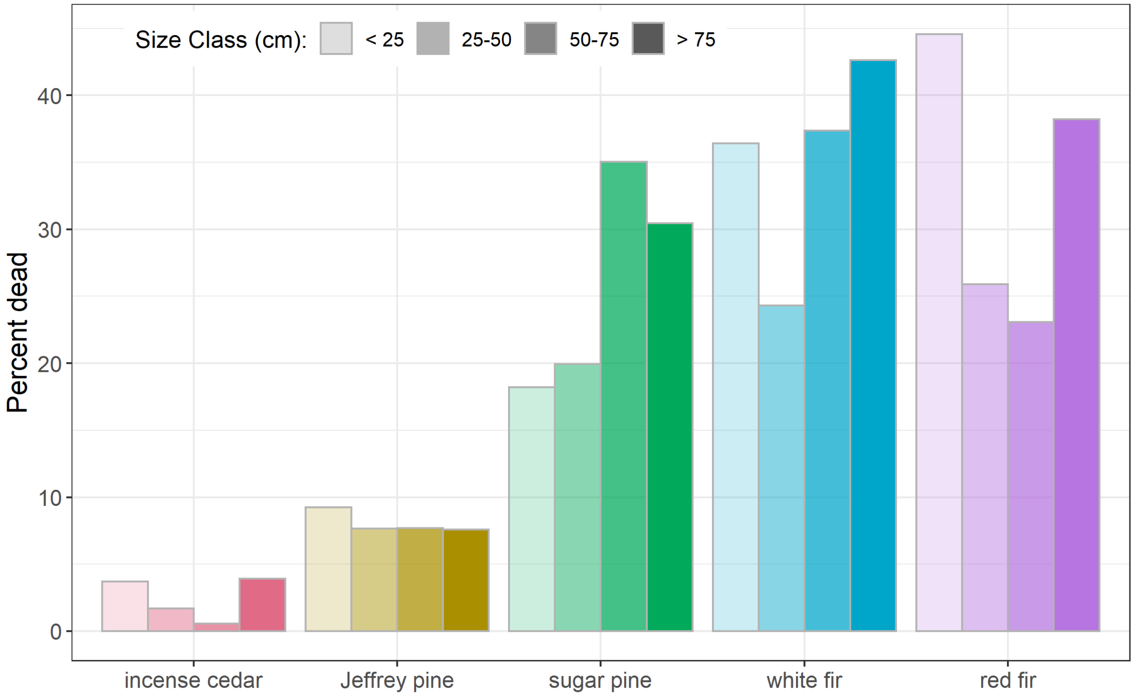

Figure 2. Mortality of five conifer species during the 2012-2016 drought, summarized by diameter at breast height size class.

Mortality varied by species with both firs (*Abies concolor* and *A. magnifica*) and sugar pine (*Pinus lambertiana*) having the highest rates and incense cedar (*Calocedrus decurrens*) and Jeffrey pine (*Pinus jeffreyi*) experiencing much lower mortality. For the species with higher mortality, both firs had highest rates for the smallest and larger size classes, while for sugar pine the mortality was concentrated more in the larger size classes.

We than compared mortality amongst treatment accounting for 'background' mortality. In the following figure we compared each treatment's mortality against the rates in the control with the dashed line representing the background or control rate and the graphs represent the distribution for size classes of each species.

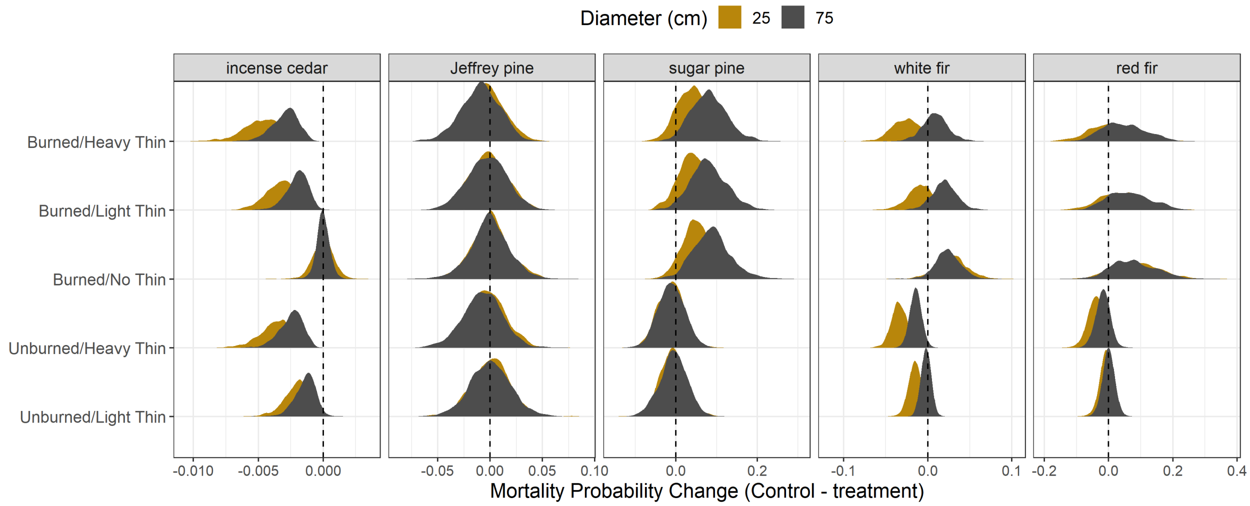

Figure 3. Indirect effect of treatment on drought-mortality on five conifer species. Value distributions represent change in probability of mortality relative to no action (i.e. control – treatment) for two tree sizes. The scale of the x-axis varies among species.

Model predictions showed the indirect effect of forestry treatments on drought-related mortality varied among species and often by tree size. Relative to untreated areas, mortality of incense cedars is reduced when stands have been thinned, although absolute effect sizes are low given low rates of cedar mortality generally (Figure 3). For large cedars (75cm DBH), light thinning and burning treatments resulted in a 0.2% reduction in mortality on average (95% PI: 0.1, 0.4%), while heavy thinning and burning resulted in a slightly larger reduction (mean: 0.3%; PI: 0.1, 0.5%). The benefit of treatment on cedars was somewhat larger for any residual small trees (25cm DBH), with a 0.5% reduction in mortality on average (0.2, 0.8%) when a stand underwent a heavy thin and prescribed burn. Jeffrey pines also died at relatively low rates during the drought (Figure 2) and saw no apparent effect of treatment on mortality regardless of size class (Figure 3). Sugar pine also saw little effect of thinning on drought mortality when unaccompanied by prescribed burning. However, the species showed large increases in mortality within prescribed burn plots, especially among large trees. Relative to controls, mortality of large sugar pines is predicted to increase by 8.7% (0.6, 19.0%) within burned/no thin plots, with only marginally lower increases for burned/light thin (mean: 7.8%; PI: -0.4, 17.7%) and burned/heavy thinned plots (mean: 8.0%; PI: 0.2, 17.8%). Predicted increases in mortality were slightly lower for small sugar pines (Figure 3). Thinning treatments may reduce drought-related mortality somewhat for white fir with unburned/heavy thin treatments predicted to decrease mortality of large trees by 1.4% (0.1, 2.7%), and by 3.4% (1.7, 5.1%) in the case of small trees. In contrast, burning likely increased mortality rates among large white firs with 2.4% (-0.6, 5.5) more large individuals expected to die in burned/no thin treatments relative to controls. This increased mortality is largely offset by the benefits of thinning for small white firs (Figure 3). Thinning showed little effect on red fir mortality regardless of tree size. However, burning may substantially increase large tree mortality rates relative to the controls (7.4%) when plots were burned but not thinned, albeit with relatively high model uncertainty (PI: -4.1, 22.0%). Predictions for other treatments and for small red firs were similar.

Q3) What local factors (i.e., stem density, shrub biomass, topography, etc.) are associated with different seral patterns and greater within treatment heterogeneity?

Regeneration Density

We examined seral patterns by comparing tree regeneration between the different treatments. Initially (1-4 years post treatment), tree regeneration density displayed consistent trends in response to treatments. Shade-tolerant white fir and incense-cedar regeneration density increased dramatically in both burned and unburned understory thinned plots (Fig 4). These increases were especially pronounced for incense-cedar, exceeding pretreatment densities, and on the extreme end exceeded 5000 trees per hectare (tph) in the burned understory thinned treatments. Additionally, white fir (but not incense-cedar) regeneration increased dramatically in the burned unthinned treatments. White fir regeneration was stable in the control, and decreased in both burned and unburned overstory thin treatments. Incense-cedar regeneration density was also stable in controls, burn only treatments, and unburned overstory treatments. Only burned overstory thinned treatments had declines in both white fir and incense-cedar regeneration density. Jeffery pine and sugar pine regeneration density were an order of magnitude lower (rarely exceeding 200 tph) compared to white fir and incense-cedar. Jeffrey pine regeneration increased in both burned and unburned overstory thinned treatments, as well as burned understory thinned treatments. For all other treatment combinations, Jeffery pine regeneration did not significantly change after treatments. Curiously, sugar pine regeneration density increased across all treatment combinations (including controls), but increases were greatest in burned unthinned, unburned understory thinned, and burned overstory thinned treatments.

Overstory thinned treatments were planted immediate after treatments using 2-year old bare root seedlings of white fir, Jeffrey pine, and sugar pine. Relative planting density was proportional to pre-treatment basal area of the three species. The effect of planting on overall regeneration density was low for white fir, but resulted in a significant initial increase in regeneration density for Jeffery pine and sugar pine.

Mid-term (9-11 years post treatment), initial relative densities by species and treatment tree regeneration persisted, but new directional trends became apparent (Fig. 4). For white fir, initial increases in regeneration density declined in burned unthinned and understory thinned treatments. In contrast, large initial increases in incense-cedar regeneration density in both burned and unburned understory thinned treatments persisted. For Jeffrey pine, regeneration densities had little change, with increases in both burned and unburned overstory thinned treatments, as well as burned understory thinned treatments, relative to pretreatment. Likewise, sugar pine regeneration densities had little change compared to initial responses after treatment. The effect of planting on overall regeneration density was still low for white fir, but resulted in a significant increase in regeneration density for Jeffery pine and sugar pine.

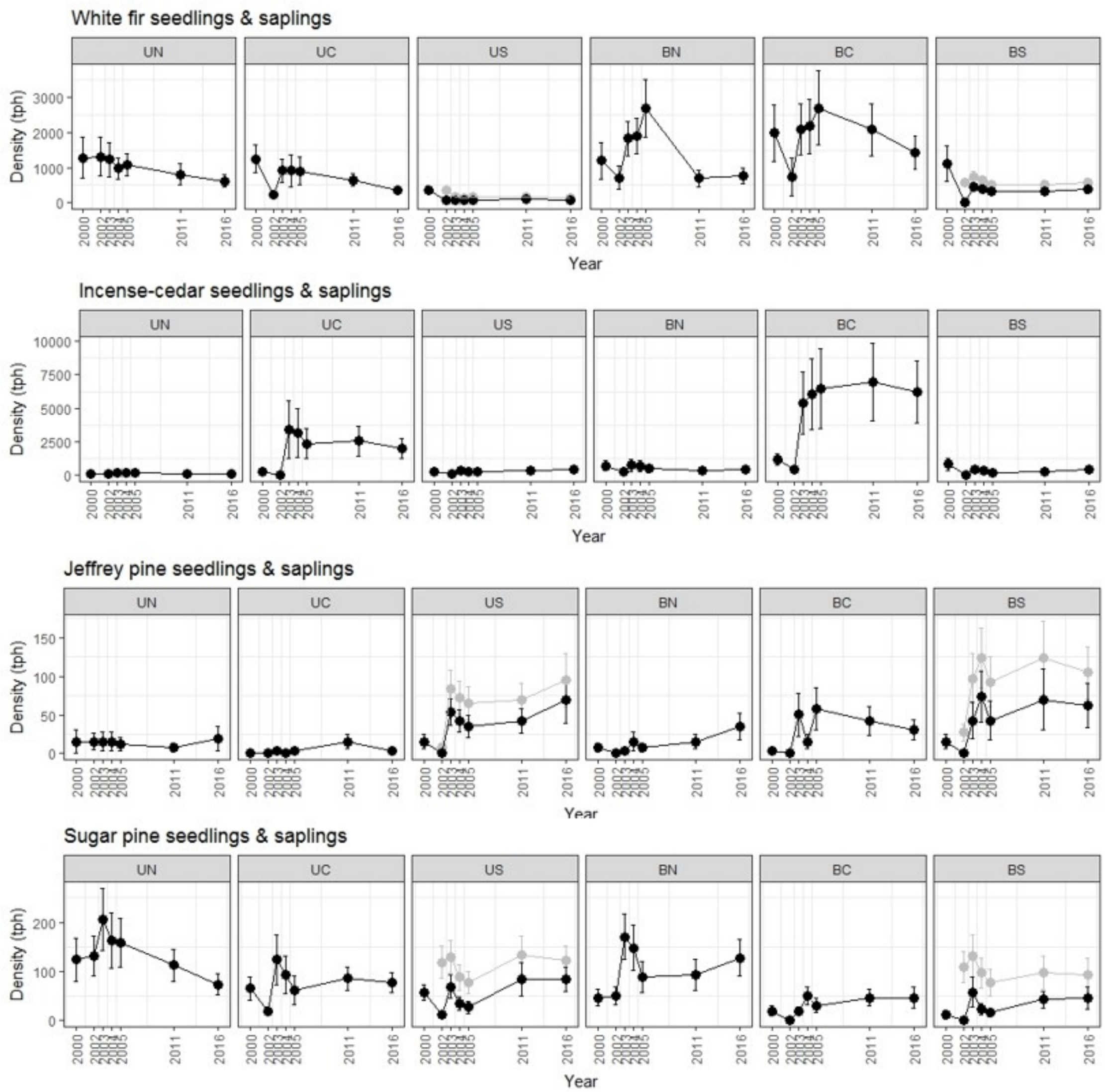

Figure 4. Regeneration density (tph) by species and treatment over time. Error bars represent standard deviation of regeneration density. Black lines are natural regeneration, grey lines are the combination of natural and planted regeneration density for species and treatment combinations where seedlings were planted. See abbreviation list for the treatment codes.

Longer-term trends (15-17 years after treatment) noticeably differed from initial and mid-term regeneration patterns (Fig. 4). Initial dramatic increases of white fir regeneration in burned unthinned and burned understory thinned treatments had largely disappeared, returning to pretreatment levels. Additionally, regeneration density of white fir in all other treatments (including controls) had declined below pretreatment levels. In contrast to long-tern declines seen for white fir, high incense-cedar regeneration density persisted in understory thinned treatments. For Jeffrey pine, regeneration densities exceeded pretreatment levels for all treatments (except controls and unburned understory thinned), with the greatest increases in both burned and unburned overstory thinned treatments. Interestingly, Jeffrey pine regeneration density in the burned unthinned treatment displayed a gradual long-term increase, such that after 15 years, regeneration density was noticeably greater than pretreatment levels, and this trend would not have been apparent without long-term data. Lastly, planted white fir, Jeffrey pine, and sugar pine did not result in increased regeneration density after 15 years.

We also investigated how the heterogeneity of overall regeneration density varied by treatments over time. We calculated the coefficient of version (CV) of regeneration density at the plot-level as a metric of regeneration heterogeneity. Initially, treatments increased heterogeneity of tree regeneration, most notably in unburned thinned treatments (Fig. 5). However, these increases in heterogeneity were short lived, with heterogeneity declining across all treatments after 15 years. In particular, regeneration heterogeneity 15 years after treatments in unburned overstory thinned and burned overstory thinned treatments was lower than pretreatment levels. In the burned overstory thinned treatment, planting appeared to lower regeneration heterogeneity, although this effect with not significant after 15 years.

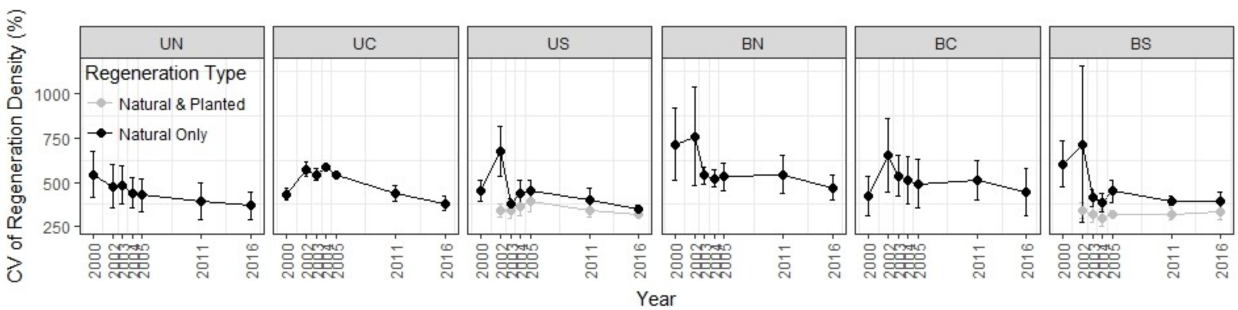

Figure 5. Coefficient of variation (CV) of overall regeneration density by treatment over time. Error bars represent standard deviation of regeneration density. Black lines are natural regeneration, grey lines are the combination of natural and planted regeneration density for treatment combinations where seedlings were planted. See abbreviation list for the treatment codes.

Lastly, we examined how natural regeneration density by treatment varied in relation to pretreatment vegetation type (closed canopy forest, shrub dominated by *Ceanothus cordulatus*, and bare ground). For both the control and overstory thin treatments, trends in regeneration density over time were similar across the pretreatment vegetation three types (Fig. 6). However, for understory thinned treatments and burned unthinned treatments, increases in regeneration density disproportionally occurred on sites that were originally closed canopy forest. On burned and understory thinned treatments, regeneration density dramatically increased on both closed canopy and shrub dominated sites, suggesting this treatment was the only one whose regeneration patterns disrupted preexisting vegetation patch types.

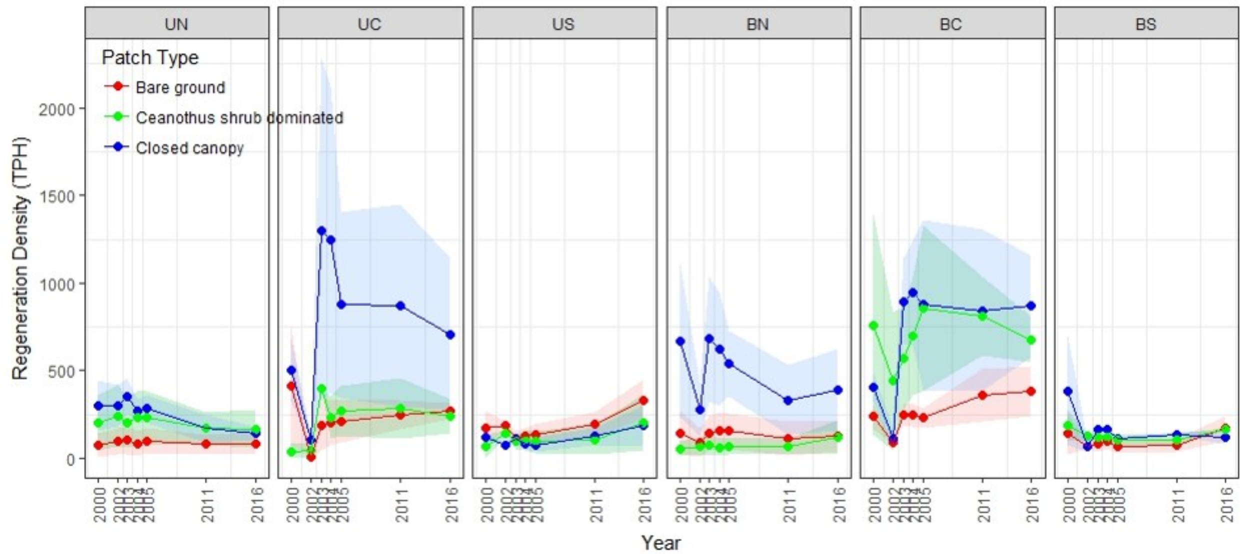

Figure 6. Overall regeneration density (tph) by treatment and pretreatment vegetation type over time. Colored areas represent standard deviation of regeneration density. See abbreviation list for the treatment codes.

We also examined how variability in microsite conditions varied between treatments. We quantified and compared differences in the light and soil moisture resources to assess treatment differences (Table 1).

Table 1: Mean values with standard errors in parentheses for environmental variables in each of Teakettle's different treatments. Values within a row with different superscripts are significantly different ($p<0.05$). ISF, DSF, and TSF are the proportions of indirect, direct, and total light compared to open.

Environ. Variable	UN	UC	US	BN	BC	BS
ISF	0.29 (0.01)^{d}	0.38 (0.01)^{c}	0.50 (0.01)^{b}	0.28 (0.01)^{d}	0.42 (0.01)^{c}	0.55 (0.01)^{a}
DSF	0.35 (0.02)^{c}	0.44 (0.02)^{b}	0.58 (0.02)^{a}	0.36 (0.02)^{c}	0.50 (0.02)^{b}	0.65 (0.02)^{a}
TSF	0.35 (0.02)^{c}	0.44 (0.02)^{b}	0.57 (0.02)^{a}	0.35 (0.02)^{c}	0.49 (0.02)^{b}	0.64 (0.02)^{a}
H2O% June	8.6 (0.9)^{b}	11.2 (0.8)^{ab}	12.9 (1.2)^{a}	9.0 (0.7)^{b}	11.8 (1.1)^{ab}	9.1 (0.5)^{b}
H2O% Aug.	4.3 (0.2)^{a}	7.3 (0.3)^{bc}	7.9 (0.5)^{c}	4.7 (0.2)^{a}	6.8 (0.3)^{bc}	5.9 (0.2)^{ab}
Litter %cvr	61.6 (3.6)^{a}	57.8 (3.8)^{ab}	46.0 (3.6)^{b}	67.6 (3.6)^{a}	47.2 (3.7)^{b}	16.5 (2.6)^{c}
Soil %dist.	0	7.5	10.5	0	12	18

In an earlier paper (Ma et al. 2010), we documented microclimate variability within and between plots, finding that local variability in tree density was highly correlated with temperature variance, while slope steepness, aspect and litter depth were associated with soil moisture. These patterns held into the 2017 measurements, which did not significantly differ from Ma's results.

Q4) For each of the treatments, what local factors are associated with reduced radial increment growth, tree resilience to drought, and tree mortality?

We assessed tree growth response using increment cores from 720 sampled trees. Cores were prepared using standard procedures (i.e., glued to wooden mounting sticks, sanded to clearly delineate ring boundaries), measured to the nearest 0.001 mm (i.e., a calibrated color flatbed scanner [1200 dpi] and WinDENDRO version 2017a software [Regent Instruments Canada Inc.]) and cross-dated (using the dplR package in R [Bunn 2008]). Annual basal area increment (BAI) values were calculated from each ring width series and associated tree DBH values using the dplR package in R, and BAI values for each series (tree) were normalized by their standard deviation (sBAI).

From 1950 until treatments in 2000 - 2001, sBAI varied by year, but did not display any strong directional trends (Fig. 7). Understory and overstory thinning resulted in large increases in sBAI from 2002 – 2011, while burning alone resulted in initial declines in sBAI. During the 2012 – 2016 drought, sBAI declined in all treatments, but was still noticeably greater than pretreatment levels for thinned treatments, indicating that thinning resulted in a persistent increase in growth for residual trees that was sustained during the drought.

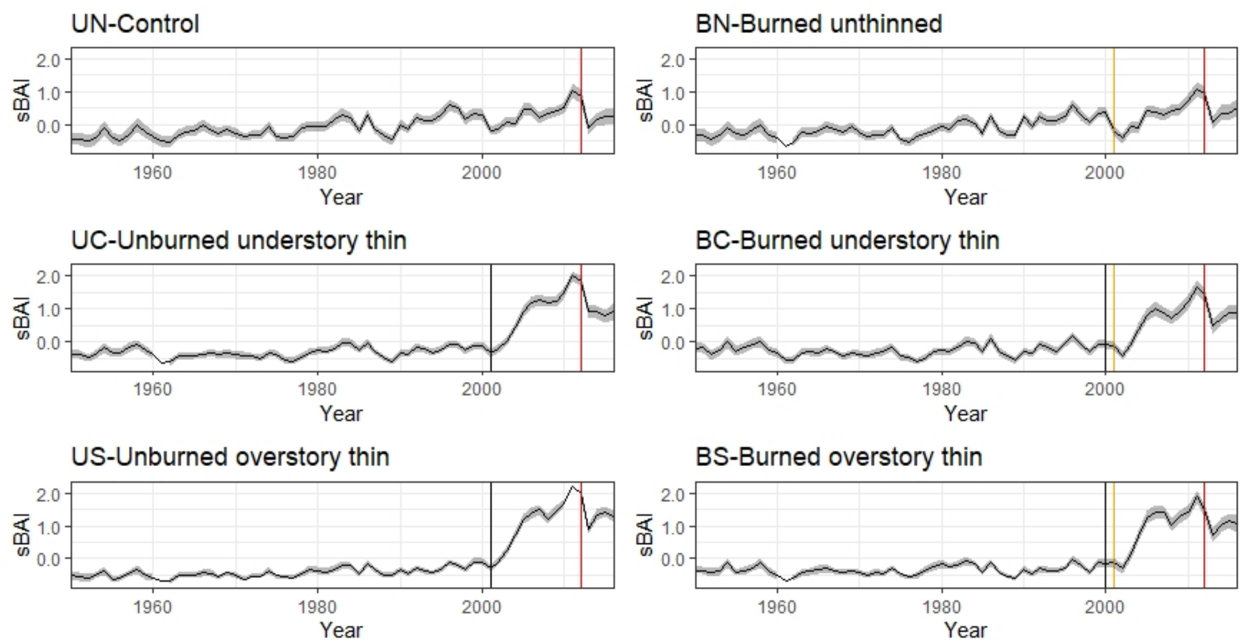

Figure 7. Standardized basal area increment (sBAI) by treatment during the 1950 – 2017 time period. Black line is the mean sBAI by treatment, grey shading is the 95% confidence interval of sBAI. Vertical lines represent the year of harvest (black), year of prescribed burning (yellow), and onset of drought in 2012 (red). See abbreviation list for the treatment codes.

From BAI values, three different growth response and resistance metrics were calculated for analyses focusing on growth response after treatments (RTRT), growth response to treatments during the drought (RTRTD), and growth resistance to the drought (RD). The RTRT variable was calculated as the average 2006-2011 BAI divided by the average pretreatment 1995-1999 BAI. The RTRTD variable was calculated as the average BAI during the drought (2012-2016) divided by the average 1995-1999 BAI. The third response variable RD was calculated as the average 2012-2016 BAI divided by the average 2006-2011 BAI, as described by (Lloret et al. 2011). These metrics enabled us to assess short-term treatment effects, if treatment effects were sustained during the drought, and if treatments were associated with changes in growth resistance to drought.

To evaluate treatment effects and species effects on tree growth response and resistance metrics at the stand-level, we fit linear mixed effects (LME) models on the resistance metrics described above using the nlme package in R (Pinheiro et al. 2017). The models included three fixed effects (burn, thin, species) and all possible interactions among them. Individual treatment plots were included as a random effects term, due to unequal sampling of trees in each replicate plot. Three different LME models with the same fixed effects, interaction terms, and random effects were developed to assess fixed effects and their interactions on growth response to treatments (RTRT), growth response to treatments during the drought (RTRTD), and growth resistance to the drought (RD). Multiple comparisons tests using Tukey's adjustment compared levels of significant fixed and interaction effects in LME models. Thinning, species, and thinning x species interactives significantly affects initial growth responses (RTRT), but burning did not (Table 2, Fig 8-10). Initial growth responses were comparable for understory and overstory thinning. Growth responses during the drought (RTRTD) were also driven by thinning, but with only a suggestive ($p = 0.0633$) thinning x species interaction effect. As with initial treatment responses, the treatment response during the drought was comparable for understory and overstory thinning. There were no significant drivers of the resistance (RD) growth metric. These findings confirm the visual assessment of sBAI trends, indicating that thinning resulted in a persistent increase in growth for residual trees, and that increased growth was sustained during the drought. Additionally, understory and overstory thinning had comparable growth responses, indicating a wide range of stand-level thinning intensities may result in similar persistent increases in growth not reversed by drought. Lastly, species differences in growth response during the drought appeared to become more apparent with increased thinning intensity.

Table 2. Summary of mixed effects models of treatment and species predictors of initial growth response to treatment (RTRT), response to treatment during the 2012-2016 drought (RTRTD), and resistance to the drought (RD).

Response variable	Explanatory Variable	DF	F	*p*
R_{TRT}	BURN	1, 12	2.9807	0.1099
	THIN	2, 12	34.5543	<0.0001
	SPECIES	3, 676	3.0702	0.0273
	BURN x THIN	2, 12	1.0709	0.3733
	BURN x SPECIES	3, 676	0.6343	0.5930
	THIN x SPECIES	6, 676	3.3408	0.0030
	BURN x THIN x SPECIES	6, 676	1.1255	0.3456
R_{TRTD}	BURN	1, 12	3.1473	0.1014
	THIN	2, 12	21.6254	0.0001
	SPECIES	3, 676	1.4592	0.2245
	BURN x THIN	2, 12	1.0530	0.3790
	BURN x SPECIES	3, 676	0.7134	0.5442
	THIN x SPECIES	6, 676	2.0020	0.0633
	BURN x THIN x SPECIES	6, 676	1.2767	0.2657
R_D	BURN	1, 12	0.0000	0.9985
	THIN	2, 12	0.1240	0.8844
	SPECIES	3, 676	0.9680	0.4072
	BURN x THIN	2, 12	0.3200	0.7321
	BURN x SPECIES	3, 676	1.1100	0.3441
	THIN x SPECIES	6, 676	0.2430	0.9621
	BURN x THIN x SPECIES	6, 676	0.5340	0.7827

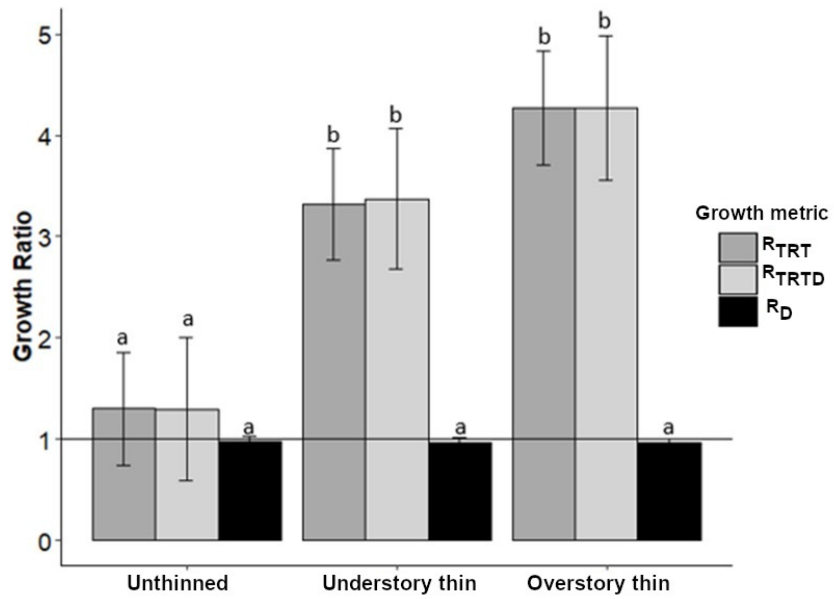

Figure 8. Growth metrics by thinning treatment. Error bars represent the 95% confidence interval of growth metrics. Letters above each bar denote significance compared to different factor levels of the same growth metric based on Tukey HSD test. RTRT = initial growth response to treatment, RTRTD = response to treatment during the 2012-2016 drought, RD = resistance during the 2012-2016 drought.

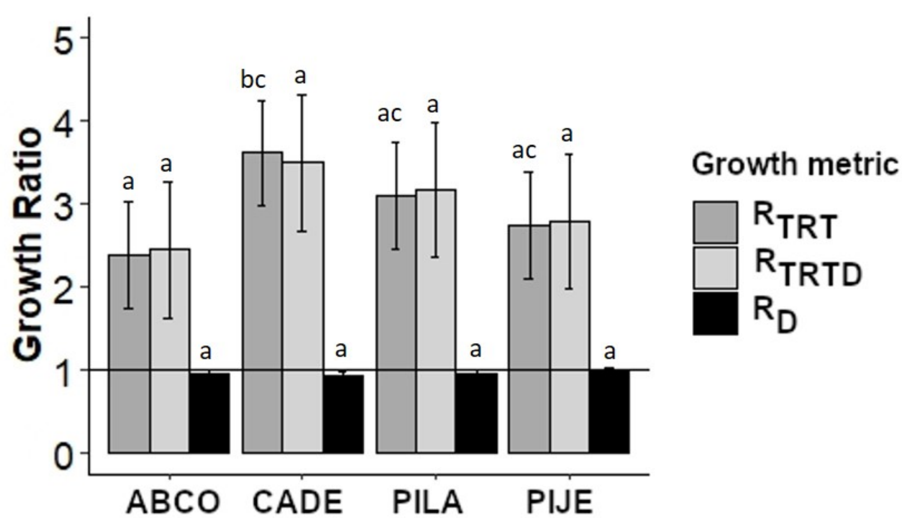

Figure 9. Growth metrics by species. Error bars represent the 95% confidence interval of growth metrics. Letters above each bar denote significance compared to different factor levels of the same growth metric based on Tukey HSD test. See list of abbreviations for species codes. RTRT = initial growth response to treatment, RTRTD = response to treatment during the 2012-2016 drought, RD = resistance during the 2012-2016 drought.

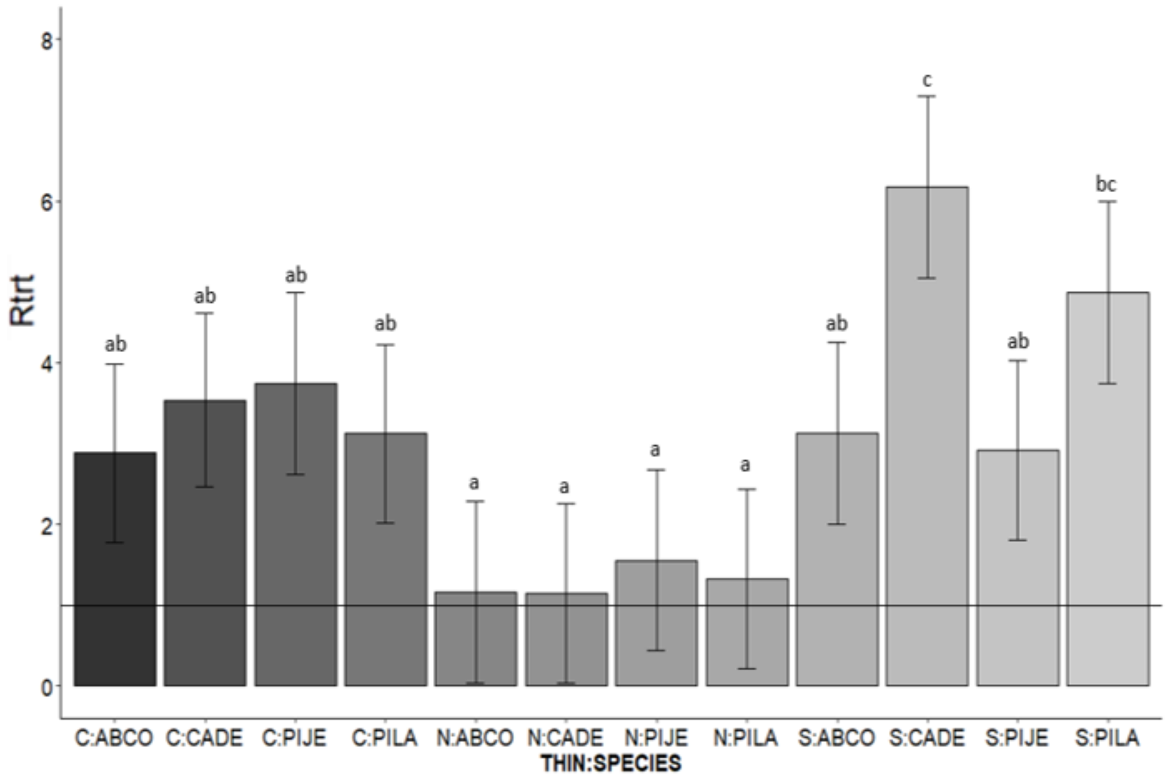

Figure 10. Growth metrics by species x thinning combination. Error bars represent the 95% confidence interval of growth metrics. Letters above each bar denote significance compared to different factor levels of the same growth metric based on Tukey HSD test. RTRT = initial growth response to treatment, RTRTD = response to treatment during the 2012-2016 drought, RD = resistance during the 2012-2016 drought.

To assess growth responses and drought resistance at the tree-level, we used Random Forest (RF) ensemble machine learning to quantify the relative importance of treatments, local competition, tree attributes, and topographic variables on tree-level growth responses during the drought (RTRTD). We used RF supervised machine learning algorithms with the randomForest package in R (Liaw and Wiener 2002). We included the following potential predictor variables: tree species, tree DBH, tree height, live crown ratio, crown canopy class, tree-level growth space using Thiessen polygon area calculated from stem maps, level of thinning, level of burning, elevation, slope, cosine transformed aspect, and topographic position index. Significant explanatory variables were selected within the RF analysis using a two-stage selection procedure in the VSURF package in R (Genuer et al. 2010, Genuer et al. 2016). RF analysis found that tree DBH, and change in growth space from pretreatment to 2011 were the most important predictors of growth response during the drought (Figure 11). Growing space in 2011, thinning, and moderate scale topographic position were also important predictors of growth response during the drought. While stand level analysis found clear effects of thinning on residual tree growth, RF analysis suggests it is tree level attributes such as size and growing space, not stand level thinning intensity, that may be driving growth responses.

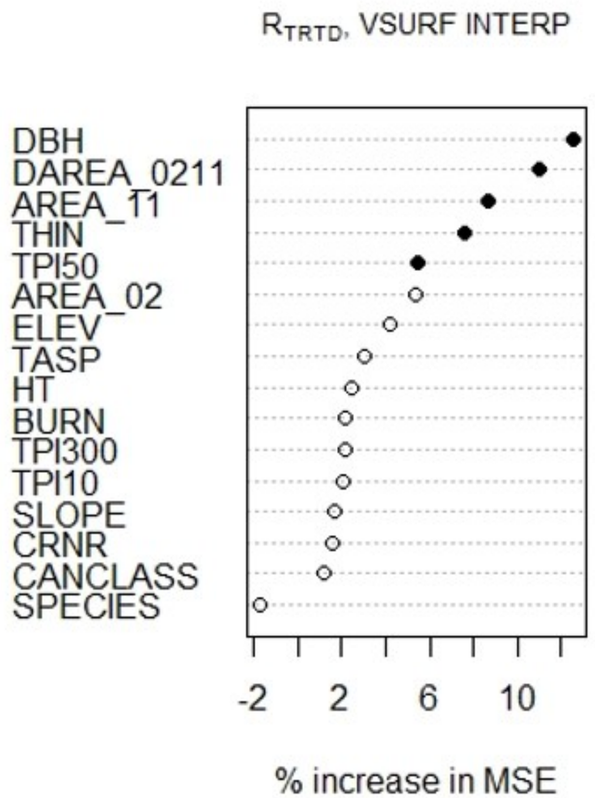

Figure 11. Random Forest analysis variable importance plot of growth response to treatment during drought (RTRTD) in relation to tree attributes, growing space, treatments, and topographic variables. Solid circles represent significant variables in the RF model based on two-stage variable selection procedures. DAREA_0211 = change in growing space from pretreatment to 2011, AREA_11 = growing space in 2011, THIN = levels of thinning, TPI50 = moderate scale topographic position index, AREA_02 = pretreatment growing space, ELEV = elevation, TASP = cosine transformed aspect, HT = tree height, BURN = levels of burning, TPI300 = large scale topographic position index, TPI10 = fine scale topographic position index, SLOPE = slope, CRNR = live crown ratio, CANCLASS = canopy position class, SPECIES = species.

Q5) How does predicted fire behavior and effects under wildfire conditions vary within treatments? What specific characteristics (e.g., shrub cover, dense tree regeneration) are associated with undesirable predicted fire behavior?

Treatment effects on susceptibility to high-severity fire indicate that burn treatments are most susceptible because of fuel loading from litter and dead small trees, now ‘jack strawed’ on the ground. Most of the plots have a high-level of tall (>2 m) ceanothus cover that the models consider flammable, which is the case during peak wildfire season. However, ceanothus rapidly uptakes any precipitation and is difficult to burn once ‘wetted’. We’ve analyzed the variability in ceanothus resistance to ignition and found ignition resistant shrubs often grow in cold air pooling and ‘funnel’ areas that may be concentrating upslope surface and subsurface water. We do not currently have a good means of incorporating this combustion temporal and spatial variability into the burn models.

We observed distinct surface fuel conditions develop following the different treatments, particularly among the different applications of prescribed fire (burn-only, understory-thin +burn, and the overstory-thin + burn treatments). The primary difference among these burn treatments was in the abundance and spatial patterns of understory shrubs (primarily *Ceanothus* sp. and *Arctostaphylos* sp.). The overstory-thin + burn treatment had the highest overall shrub cover and largest contiguous patches of shrubs. The understory-thin + burn was intermediate for both overall abundance and patch size, while the burn-only had the lowest for both. In fact, the shrub cover in the burn-only was similar to that in the unburned treatments.

Woody surface fuels were fairly similar across the three treatments, with slightly lower coarse woody fuels in the overstory-thin + burn. Modeled fire behavior using the Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE) suggest three points about the likelihood of overstory tree torching under wildfire conditions: 1) the untreated control has the highest potential of all the treatments; 2) the understory-thin + burn has the second highest potential, given the combination of moderately high shrub cover and moderate tree density; and 3) The overstory-thin + burn has high potential surface fire behavior, but given the low residual tree density and the high height-to-live-crown of the residual trees we would expect an intermediate level of overstory tree torching.

Conclusions and Management/Policy Implications

Our results have sobering implications for fuel treatments widely used by managers. Prescribed fire, which is widely considered the most beneficial treatment for forest restoration, in the longer -term increased fuel loading and potential reburn severity, while reducing some tree species (fir and sugar pine) resistance to bark beetle mortality. In contrast, thinning increased tree resilience to drought, and the type of stand-level thinning appeared to matter less than its localized influence on neighborhood density. Given the historic fire frequency of Sierra Nevada mixed-conifer forests and changes that have occurred with fire exclusion, restoring forest structural heterogeneity across scales (from the site to the landscape) will help reduce the likelihood of transitioning from one homogenous state to another. Overall, we found that high levels of fuel inputs and vigorous shrub response to burning suggest that once fire is used, it must be repeatedly employed to initially restore and subsequently maintain a diverse fuel, understory, and microclimate environment.

Future Research

We recently applied the second round of prescribed fire treatments to Teakettle, 16 years after the original burn, in line with the historic fire return interval. We are particularly interested in whether 2nd entry burning will show more positive effects on the understory, fuels, and tree growth response than following the initial burn. We also want to determine what light environment, caused by canopy cover reduction, is associated with vigorous shrub response in the thin-only treatments. In the burns, shrubs dramatically increase with increasing burn intensity, but the response in thinning treatments seems to be more aligned with changes in understory light. For managers, understanding what level of overstory canopy reduction may trigger vigorous shrub growth, could be an important consideration in creating more fire resilience future conditions. Finally, we want to identify what fire effects are most associated with reduced radial growth and drought susceptibility. Is it the highest temperature, burn duration, litter and duff reduction or bole and crown scorch? A better understanding of what is most influential in reducing tree resilience might help identify more optimal ignition and burn patterns when applying prescribed fire.

Literature Cited

Bunn, A.G. 2008. A dendrochronology program library in R (dplR). Dendrochronologia 26:115-124.

Genuer, R., J.-M. Poggi, and C. Tuleau-Malot. 2010. Variable selection using random forests. Pattern Recognition Letters 31:2225–2236.

Genuer, R., J.-M. Poggi, and C. Tuleau-Malot. 2016. VSURF: variable selection using random forests. R package version 1.0.3. https://cran.r-project.org/web/packages/VSURF/index.html

Goodwin, M., M. North, H. Zald, and M. Hurteau. 2018. The 15-year post-treatment response of a mixed-conifer understory plant community to thinning and burning treatments. Forest Ecology and Management 429: 617-624.

Innes, J.C., M.P. North, and N. Williamson. 2006. Effect of thinning and prescribed fire restoration treatments on woody debris and snag dynamics in a Sierran old-growth, mixed-conifer forest. Can. J. For. Res. 36: 3783-3793.

Liaw, A., and M.Wiener. 2002. Classification and regression by randomForest. R News 2:18–22.

Pinheiro J.D., S. Bates, D. DebRoy, D. Sarkar, and R. C. Team. 2017. nlme: linear and nonlinear mixed effects models. https://cranr-project.org/web/packages/nlme/index.html

Lloret, F., E.G. Keeling, and A. Sala. 2011. Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests. Oikos 120: 1909-1920.

Wayman, R.B. and M. North. 2007. Initial response of a mixed-conifer understory plant community to burning and thinning restoration treatments. For. Ecol. Man. 239: 32-44.

Appendix A: Contact Information for Key Project Personnel

Malcolm North, malcolm.p.north@usda.gov, 530-902-8135

Harold Zald, hsz16@humboldt.edu, 707-826-5484

Brandon Collins, bcollins@berkeley.edu, 510-664-7027

Matthew Hurteau, mhurteau@unm.edu, 505-277-0863

Appendix B: List of Completed and Planned Publications and Science Delivery

Articles in peer-reviewed journals

Goodwin, M., M. North, H. Zald, and M. Hurteau. 2018. The 15-year post-treatment response of a mixed-conifer understory plant community to thinning and burning treatments. Forest Ecology and Management 429: 617-624.

Steel, Z., M. North, M. Goodwin, M. Hurteau, and H. Zald. In prep. Mixed conifer tree growth and mortality during drought and 15 years after fuels treatment.

Callahan, C. H. Zald, M. North and M. Hurteau. In prep. Effects of thinning and prescribed burning on tree Resistance to extreme drought in a Sierra Nevada mixed-conifer forest, California USA.

Zald, H.S.J., M.J. Goodwin, M.P. North, M.D. Hurteau, and A.N. Gray. In prep. Long-term tree regeneration responses to thinning and prescribed burning in a Sierra Nevada mixed conifer forest. Forest Ecology and Management.

Zald, H.S.J., C.C. Callahan, M.P. North, and M.D. Hurteau. 2019. In prep. Stand and tree-level effects of thinning and prescribed burning on tree growth responses to extreme drought in a Sierra Nevada mixed-conifer forest, California USA. Forest Ecology and Management.

Graduate Thesis

Callahan, C.C. 2019. Effects of Thinning and Prescribed Burning on Tree Resistance to Extreme Drought in a Sierra Nevada Mixed-Conifer Forest, California USA. MS Thesis, Humboldt State University, 56 p.

Conference Presentations

Zald, H.S.J., M.J. Goodwin, M.P. North, M.D. Hurteau, and A.N. Gray. 2019. Tree regeneration and understory vegetation responses to second entry prescribed burns in a Sierra Nevada mixed conifer forest. Ecological Society of America annual meeting. August 15 2019, Louisville, KY USA

Zald, H.S.J., C.C. Callahan, M.P. North, and M.D. Hurteau. 2019. Stand and tree-level effects of thinning and prescribed burning on tree growth responses to extreme drought in a Sierra Nevada mixed-conifer forest, California USA. 8th International Fire Ecology and Management Congress. November 21 2019, Tucson, AZ USA.

Jaffe, M., H. Northrop, F. Malandra, J. Levine, D. Krofcheck, M. Hurteau, B. Collins, and M. North. Modeling shrub consumption in prescribed fire. Tucson, AZ. 18-21-November, 2019.

Presentations/webinars/outreach/science delivery

Much of the work for this research project has helped inform better management practices, which both Hurteau and North have incorporated into their outreach. This includes a number of two-page summaries on this research, as well as links to media stories.
Hurteau: http://www.hurteaulab.org/outreach.html
North: https://northlab.faculty.ucdavis.edu/media/

Field demonstration/tour summaries

In the spring of 2016 we held a workshop for the Sierra Nevada Conservancy, California Air Resources Board, CAL FIRE, and California EPA at the Teakettle Experimental Forest. On that tour we talked about the role of forests in mitigating climate change and the risks posed by wildfire and drought-induced mortality. The trip was successful in large part to the logistical support provided by the California Conservation Corps. The group was particularly interested in the tree mortality response to the (then) ongoing drought and whether the 2000-2001 fuel reduction treatments were influencing radial growth and mortality patterns.

Figure 12: Malcolm North provided a history of the Experimental Forest and the Teakettle Experiment.

This meeting had many of the policy administrators involved in setting the forest carbon sequestration standards for California's developing carbon credit market. One of the concerns with stabilizing forest carbon in large trees is that it requires a reduction in forest density through thinning or prescribed fire, treatments which incur an immediate carbon reduction. A question that arouse is the role of fire emissions in these calculations.


Figure 13: Klaus Scott from the California Air Resources Board shared with us some recent analyses of wildfire emissions from large fires in California.

Appendix C: Metadata

Metadata for the 2016-2018 re-measurement of the Teakettle plots has been provided to J.F.S.P. Data is archived at
https://datadryad.org/stash/dataset/doi:10.5061/dryad.8931zcrm7?invitation=0NX8p-64bpqOchUBbC5mKA